Development of a UAV-based Global Ozone Lidar Demonstrator (GOLD)

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***Abstract* - A compact ozone (O_3) and aerosol lidar system is under development for conducting global atmospheric investigations from an Uninhabited Aerial Vehicle (UAV) and for enabling the development of a space-based O_3 and aerosol lidar. The objective of this activity is to develop and test a UAV-based Global Ozone Lidar Demonstrator (GOLD) that will enable revolutionary new global Earth system science investigations from UAV platforms and from space. GOLD will incorporate the most advanced technology to produce a compact, autonomously operating O_3 and aerosol Differential Absorption Lidar (DIAL) system for a UAV platform. The GOLD system leverages the most advanced Nd:YAG and optical parametric oscillator laser technologies and advanced receiver optics, detectors, and electronics. Significant progress has been made toward the development of the GOLD system, and this paper describes the objectives of this program and the design of the GOLD system.**

I. INTRODUCTION

Global ozone measurements are needed across the troposphere with high vertical resolution to enable comprehensive studies of continental and intercontinental atmospheric chemistry and dynamics which are affected by diverse natural and human-induced processes. The development of a UAV-based GOLD system is an important step in enabling a space-based O_3 and aerosol lidar and for conducting unique UAV-based large-scale atmospheric investigations.

The GOLD system will incorporate the most advanced laser technology developed under the NASA Laser Risk Reduction Program (LRRP) to produce a compact, autonomously operating O_3 and aerosol DIAL system for a UAV platform. This system will leverage advanced Nd:YAG and optical parametric oscillator (OPO) laser technologies being developed by ITT Industries under the LRRP, and advanced receiver optics and electronics and DIAL control system technologies developed by the GOLD team including ITT and Welch Mechanical Designs. All GOLD sub-systems will be integrated and ground tested at NASA Langley and flight tested on a NASA UAV.

The development of the GOLD system was initiated as part of the NASA Instrument Incubator Program in December 2005, and great progress has been made towards completing major GOLD subsystems. ITT has nearly completed the development of the high-power Nd:YAG pump laser and the OPO nonlinear conversion modules for generating the O_3 DIAL wavelengths of 290 and 300 nm and the aerosol visible wavelength at 532 nm. NOAA has completed detector evaluations for use in the GOLD system. Welch Mechanical Designs has a design concept for integrating GOLD into the external pod that will be hung under the NASA Dryden IKHANA UAV. Science objectives for the GOLD system and details of the GOLD system design and development are discussed in the following sections.

II. BACKGROUND FOR GOLD DEVELOPMENT

A. Enabling Global Atmospheric Science Investigations

The development of the GOLD system is a revolutionary step toward conducting global atmospheric research with UAV platforms, and it is an enabling step in the development of a space-based O_3 and aerosol lidar system. Both of these steps will be important contributions to the long-range objectives of NASA's Earth System Science Research Program.

A UAV-based O_3 and aerosol differential absorption lidar (DIAL) system, such as GOLD, will be able to conduct global atmospheric science investigations that will complement and extend those being conducted from the Aura satellite by providing high vertical resolution O_3 and aerosol measurements that can be used to validate measurements from Aura and to observe atmospheric features and processes that take place on vertical scales that are too small to resolve with current passive sensors. In addition, the simultaneous measurements of O_3 and aerosols can provide insights into atmospheric composition, dynamics, and source/sink processes that are unavailable to the passive satellite instruments. A UAV-based O_3 DIAL system will provide a greater opportunity to study global tropospheric and stratospheric O_3 processes, including stratosphere-troposphere exchange, than can be accomplished through infrequent, major airborne field experiments using large platforms, such as the NASA DC-8 aircraft. The UAV-based GOLD system will be an intermediate step towards the development of a space-based O_3 DIAL system which will truly provide global O_3 and aerosol measurements.

Tropospheric chemistry is considered to be the 'next frontier' for atmospheric chemistry, and understanding and predicting the global influence of natural and human-induced effects on tropospheric chemistry will be a major challenge for atmospheric research over the next couple of decades. In particular, obtaining the global distribution of tropospheric O_3 with high vertical resolution (1-3 km) would greatly enhance the understanding of atmospheric processes related to transport, dynamics, O_3 production and loss, atmospheric radiation balance, and photochemistry [1]. The simultaneous high vertical resolution (100 m) measurements of aerosol and cloud distributions along with the O_3 measurements provide important complementary information about air mass types and their origin, evolution, chemistry, and transport as has been demonstrated in many NASA Global Tropospheric Experiment (GTE) field missions (see e.g., [2-5]).

B. Advancing Airborne Ozone Lidar Technology

Development of the GOLD system represents a critical step in both advancing the technological readiness of a space-based O_3 DIAL system and providing new revolutionary global atmospheric composition investigations from UAV platforms. The GOLD system will use the DIAL technique for the measurement of atmospheric O_3 profiles and the standard backscatter lidar technique for simultaneous measurement of aerosol scattering ratio profiles [6,7]. The capability of the DIAL technique for atmospheric O_3 and aerosol profiling has been demonstrated with NASA Langley's Airborne UV DIAL System over the past 27 years (see e.g., [2-9]). This system has participated in 6 stratospheric missions and 20 tropospheric missions to study O_3, aerosols, and clouds. An example of the measurement capability of this method for O_3 profiling is shown in Fig. 1. This distribution represents an average atmospheric cross section obtained from O_3 measurements from the airborne UV DIAL system operating simultaneously in the nadir and zenith modes from the NASA DC-8 aircraft over the western Pacific during the GTE Pacific Exploratory Mission conducted during February-March 1994 (PEM West B). This figure illustrates the complex combination of dynamics and chemistry that contributes to the O_3 budget in the troposphere and that varies dramatically with latitude and altitude (see e.g., [2, 3, 5]).

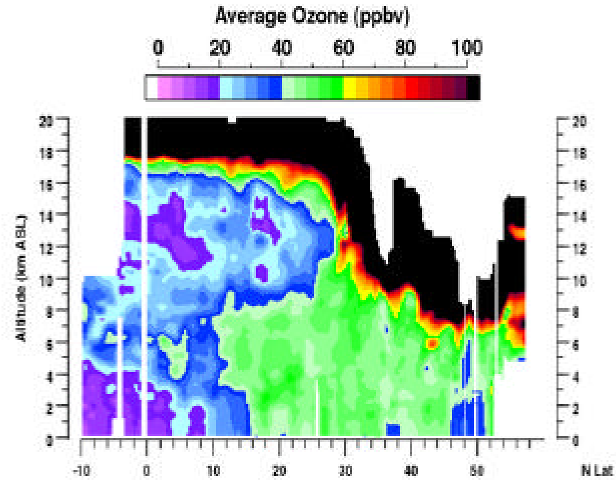

Fig. 1. Average O_3 distribution derived from airborne lidar measurements over western Pacific during PEM West B.

A complete latitudinal cross section of O_3, such as the one shown in Fig. 1 (with reduced vertical resolution), could be obtained with a space-based O_3 lidar system on a single pass of the satellite

While the DIAL technique has been demonstrated for tropospheric measurements from an aircraft flying in the troposphere, the technology needed for tropospheric O_3 measurements from space is still being developed. A joint NASA-Canadian Space Agency (CSA) study has been conducted to evaluate the feasibility and technology needed for a future space-based O_3 DIAL system. Initial measurement simulations have indicated that an measurement accuracy of 10% with vertical resolution of 2 km and horizontal resolution of 200 km during night and a vertical resolution of 3 km and horizontal resolution of 300 km during the day is possible with an O_3 DIAL system operating in Low Earth Orbit (LEO) [8,10].

III. GOLD SYSTEM CHARACTERISTICS

A. GOLD Overall Characteristics

The GOLD system parameters are listed in Table I, and they include DIAL wavelengths for tropospheric O_3 investigations (290/300 nm) from the IKHANA UAV which is capable of flying at altitudes up to 12 km. The objectives of the GOLD system are to 1) use the latest technology available to demonstrate the science capability of an O_3 DIAL lidar from a UAV platform and 2) demonstrate a compact, autonomously operating O_3 DIAL system as a precursor to a space-based DIAL system.

TABLE I
GOLD SYSTEM PARAMETERS

Transmitter	
Wavelengths	290/300 nm (DIAL); 532 nm (Aerosol)
Energy	2.5 mJ (UV), 20 mJ (Aerosol)
Linewidth	50 pm
Spectral Purity	>99.0%
Repetition rate	1000 Hz
Beam divergence	0.5 mrad
Pulse width	<10 ns
Aircraft altitude	$\leq$12 km
Aircraft velocity	220 m/s
Receiver	
Area (effective)	0.105 m^2 (40-cm dia. telescope)
Field of view	1.0 mrad
Filter bandwidth	<2nm (UV) 0.5nm (532nm)
Detector efficiency (QE)	0.25(UV) 0.2(532nm)
3-Channel system	3 digitizers (2 UV, 1Vis);

A schematic diagram of the GOLD system is shown in Fig. 3. Our partners at ITT will provide a Nd:YAG laser which will pump an Optical Parametric Oscillator (OPO) module to produce the airborne wavelengths of 290 and 300 nm. In the second year we will include an advanced telescope design from Welch Mechanical Designs and high-efficiency optical filter technology from ITT. Additional information is given below for each major component of the GOLD system.

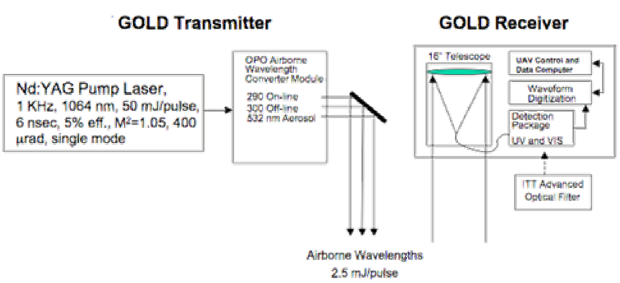

Fig. 3. GOLD system schematic

B. GOLD Laser Transmitter

The GOLD laser transmitter will use key laser technologies that have been developed under the NASA LRRP. The ITT-developed Nd:YAG pump laser is shown in Fig. 4. The pump laser consists of a single-mode YAG oscillator which is coupled into two amplifier modules producing 50 W at 1.06 micron and 1 kHz. This beam is harmonically converted to 532 and 355 nm and then sent to the OPO module, as shown in the upper right of Figure 4. The beam has an M^2 of 1.05, which is important for efficient harmonic conversion in the OPO module. The pump laser is contained in a water-cooled, mono-block enclosure with dimensions of 40x26x20cm. This compact pump laser is ideally suited for deployment on a UAV.

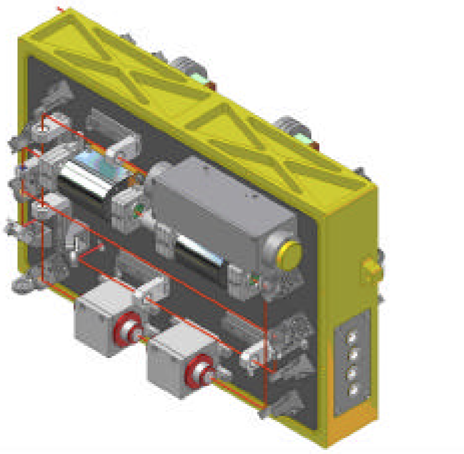

Fig. 4. Layout of Nd:YAG 50 W,1.06 µm pump laser.

The OPO airborne-wavelength module is shown in Fig. 5. The 1064-, 532- and 355-nm beams enter the OPO module from the upper left of Fig. 5. The residual 532 nm leaves the OPO module and is used as the aerosol channel for the GOLD system. The 355 and 1064 nm are harmonically mixed to create 290 and 300 nm which then exit the OPO module for transmission into the atmosphere. The conversion efficiency from the IR to airborne wavelengths is 10% resulting in 2.5 mJ at each airborne wavelength. The residual 1064- and 355-nm beams will be blocked and not used. The OPO module is enclosed in a mono-block structure of 40x26x20 cm.

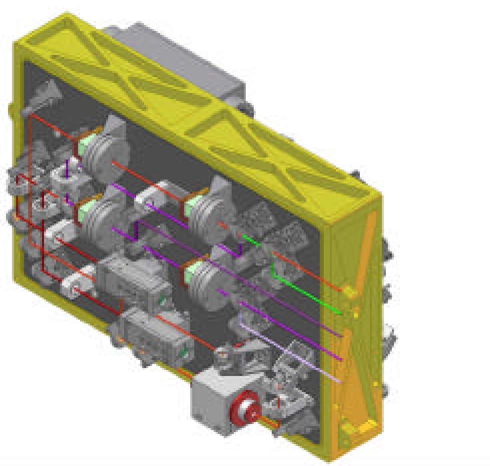

Fig. 5. Layout of OPO airborne UV converter module.

C. GOLD Receiver

We will also leverage the work being done at Welch Mechanical and NASA LaRC based on the Instrument Partnering Program (IPP) in compact, light-weight telescopes and at ITT in high-efficiency UV optical filtering systems to make the GOLD receiver system compact and efficient.

NOAA ETL has been leading the design studies regarding selection and characterization of the photomultipliers (PMTs) and associated electronics. It is critical to select the right PMTs as certain PMTs exhibit characteristics such as after-pulsing which can be detrimental to DIAL measurements. NOAA ETL has completed the evaluation of over 20 PMTs and determined that eight of the PMTs are "good" for lidar research. A specific PMT for use in the GOLD system is about to be selected.

The basic considerations for the receiver design are:

1. Accept simultaneous laser pulses in the UV (290 to 315 nm) and at 532 nm for aerosols;
2. Operate at a high PRF of 1 kHz;
3. Conform to the constraints of size, weight, power, and heat removal capacity available within the UAV payload bay;
4. Operate under varying environmental conditions encountered during flights (i.e., wide range of temperature and pressure excursions corresponding to ground and high altitude ~20 km);
5. Capable of autonomous operation – totally unattended or remotely controlled;
6. Long operational lifetime with very little or no maintenance; and
7. Based on a mature technology so that spares and replacement parts are easily available.

D. Integrated GOLD System on IKHANA

The GOLD system is being designed to be flown in a pod under the wing of the IKHANA UAV. A concept for the packaging of the GOLD system in the pod that was developed by Welch Mechanical is shown in Fig. 6. The locations of the various subsystems are indicated in the figure. The resulting GOLD system would be about 142x58x58 cm in size. This pod would be attached under the wing of the IKHANA.

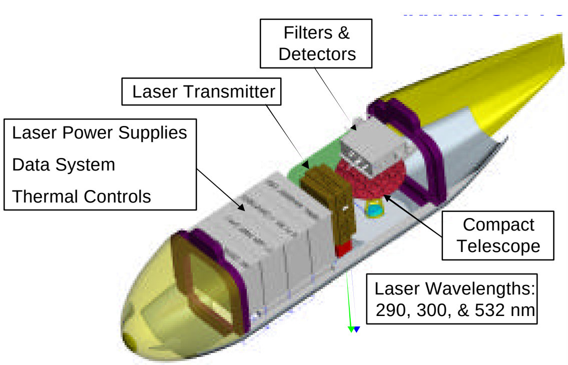

Fig. 6. Concept of GOLD system in IKHANA pod.

E. GOLD Flight Testing

Once developed and integrated into the IKHANA pod, the GOLD system will be flight tested at the NASA Dryden Flight Research Center's (DFRC) facility. The GOLD system will be flight tested during both day and night flights over the JPL Table Mountain Lidar Facility (TMLF) where ground-based lidar O_3 profile measurements will be obtained for direct comparison with GOLD O_3 measurements.

The information obtained on all these flights will prepare the GOLD system for conducting atmospheric investigations from the IKHANA and for accelerating the development of a space-based O_3 DIAL system.

IV. FUTURE DEVELOPMENT PLANS

Table II presents the key milestones leading to completion of the development and initial flight testing of the GOLD system.

TABLE II
KEY MILESTONES IN GOLD DEVELOPMENT

Pump Laser Transmitter Finished	June 2007
UV Converter Module Finished	August 2007
Grating Filter Module Completed	December 2007
System Integration Completed	August 2008
Conduct GOLD Ground Tests	October 2008
Conduct GOLD Flight Tests	December 2008

ACKNOWLEDGMENT

The authors thank the many members of the NASA Langley, NASA Goddard, ITT, Welch Mechanical, NOAA/ETL, and NASA JPL teams that are contributing to the development of the GOLD system. We also recognize and thank the NASA Earth Science Technology Office for providing the funds for the GOLD project.

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